Simulating the complete 2014 hybrid electric Formula 1 cars

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Abstract

In 2014 a new powertrain specification was introduced in to Formula 1. This new specification changed the internal combustion engine to be a 1.6 litre V6 turbocharged spark ignition engine with increased use of Energy Recovery Systems (ERS) in the form of crank and turbo-shaft motor generators, battery and associated cooling and controllers. Fuel flow limits and a limit on the total amount of fuel that can be used in the race means that efficiency of the systems has become a key focus during the development of the 2014 cars. The reduction in engine size and power from the previous season's 2.4L V8s means that the teams now rely much more strongly on the electrical energy from the ERS system to make up for the reduced internal combustion engine performance. In this work we show how a complete physical vehicle model with fully integrated subsystems (powertrain, chassis, etc) can be simulated to yield information on the consequences of a range of ERS (Energy Recovery System) configurations.

1. Introduction

The 2014 Formula 1 Technical Regulations [1], first published in July 2011, mark a significant change in the Formula 1 powertrain design for the 2014 season. Both the capacity and engine speed will be reduced compared to 2012. Turbochargers will be reintroduced for the first time since the late 1980's in an effort to maintain the power when produced by smaller engines.

The ERS will replace the previous Kinetic Energy Recovery System (KERS), delivering increased power. ERS will incorporate two motor generator units, connected to the engine crankshaft and turbocharger respectively. The gearbox will contain 8 forward gears plus reverse gear.

For 2014 the engine will be a 90 degree V6 arrangement with a 1.6 litre capacity and maximum speed of 15000rpm. The engine will have 2 inlet and 2 exhaust valves per cylinder, no variable valve timing or variable valve lift. The fuel mass flow rate must not exceed 100kg/h and below an engine speed of 10500rpm the fuel flow rate is limited according to the following formula:

$$Q\ (kg/h)=0.009N(rpm)+5 \qquad (1)$$

A single stage turbocharger will be permitted, but it must not use variable geometry or variable nozzle turbines.

The ERS will consist of:

- Motor Generator Unit – Kinetic (MGUK),
- Motor Generator Unit – Heat (MGUH),
- Energy Storage (ES).

The MGUK is comparable to KERS. The motor generator will be mechanically linked to the drivetrain with a fixed speed ratio to the crankshaft, which could be clutched. The maximum power delivered by the MGUK to propel or brake the car will be no greater than 120kW. The energy stored from MGUK to the ES will not exceed 2MJ per lap and the energy used by MGUK from the ES will not exceed 4MJ per lap. The electrical output of the MGUK will be measured.

The MGUH will be mechanically linked to the exhaust turbine of the turbocharger with a fixed speed ratio, which could be clutched.

The ES stores energy from the ERS. The form of storage is not specified by the regulations; however its total weight will be between 20 and 25kg. When the car is on track the delta between the maximum and minimum states of charge will not exceed 4MJ. Measurements will be taken at the input and output of the ES.

These changes in the powertrain specification introduce a number of challenges for the teams. The overall control strategy of the powertrain will need to be optimised to deliver the performance, fuel economy and driveability targets to enable the drivers to achieve the best lap time. At the same time the systems place an increased demand on the engine and electronics cooling systems.

2 Dymola Model Overview

2.1 Model Architecture

A complete model of the 2014 Formula 1 car including the engine, gearbox, energy recovery systems and chassis has been created in Dymola. This model is based on a number of the commercial Modelica libraries: Engines [2], VDLMotorsports [3], Alternative Vehicles [4] and uses the Vehicle Dynamics Library [5] model architecture as the framework to integrate the systems.
The top level of the vehicle model is shown in Figure 1 and consists of the driver, car, track and environmental conditions. The car model is broken down in to the major subsystems: engine, transmission, driveline, chassis and brakes. The ERS is included within the engine model.

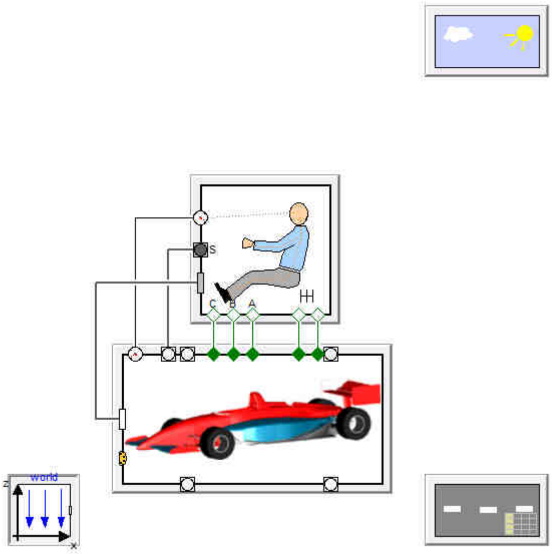

Figure 1: Complete vehicle model with open loop driver model

The model architecture makes use of the Modelica replaceable classes concept which makes it very easy to plug-in different fidelity models in to each part of the model. For instance, a simple ideal gearbox can be replaced with a high fidelity model including all of the shift mechanism details without requiring changes to the other surrounding models.

2.1 Engine Model

The Engines Library [6], [7], has been used to create a model of the 1600cc V6 turbocharged engine to be used in 2014. This model includes all the major features of the engine formula including the motor generators attached to the turbocharger and crankshaft, the intercooler and the cooling systems.
A mean-value engine model has been used to enable us to achieve real-time simulation whilst still capturing the major transient effects that influence the performance and driveability of a turbocharged engine. The model includes air-flow through the intake, turbocharger, intercooler and exhaust systems capturing the pressure and temperature transients. The mean-value combustion model takes in to account these effects together with the afr, spark timing and other factors to determine the torque output and exhaust gas temperature.

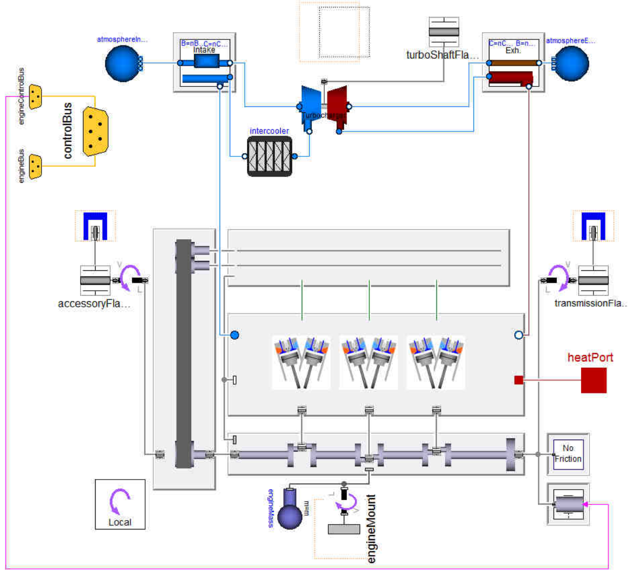

Figure 2: V6 turbocharged engine model

The Engines Library supports both mean-value and crank-angle resolved engine models and the model architecture, shown in Figure 2, is common to both. The only changes required to switch from a mean-value model to a crank-angle resolved model is to include the valve train and change the combustion model. The piston mechanics, crankshaft and intake and exhaust models do not have to be changed.
Using a crank angle resolved engine model we could investigate the torque pulsations due to each firing event and look in detail at the pressure and temperature during the engine operation. This includes being able to explore effects such as split injection, multiple injection and cylinder deactivation.
ERS Model
The engine and ERS model is shown in Figure 3. The crankshaft is coupled to an electric motor-generator through a gearset in the mGUK model. The motor-generator can be used to assist the traction torque of the engine or recharge the battery during braking. Compared to the previous (2013) specification KERS, the 2014 specification will support a higher power output from the motor-generator and allow more energy to be stored in the battery each lap.
The turbocharger shaft is also gear-coupled to an electric motor-generator and can be used to spin up the turbocharger to improve throttle response. This is modelled in the mGUH sub-system. It can also be used to control the turbocharger shaft speed and recharge the battery if excess turbocharger shaft power is available. This part of the system is called MGUH.
The model enables the control strategy to be developed and refined by exploring the overall system characteristics and

interactions. For example, the model can be used to identify when it would be possible to use the MGUH to charge the battery or power the MGUK directly without storing the energy.
The electrical systems are modelled using models from the Smart Electric Drives Library [8]. If faster models were required, table based motors could be used to replace the more detailed physical models.

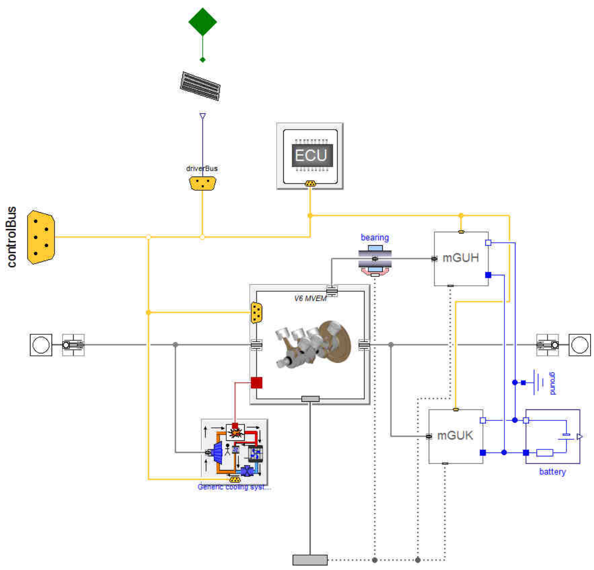

Figure 3: Engine model including ERS, ECU and cooling system

The battery model is of equivalent circuit type with heat release and variable internal resistance. The battery internal resistance is a function of temperature, state of charge (SOC) and current. Resistance related to diffusion has not been accounted for in this case but will be considered in future modelling.

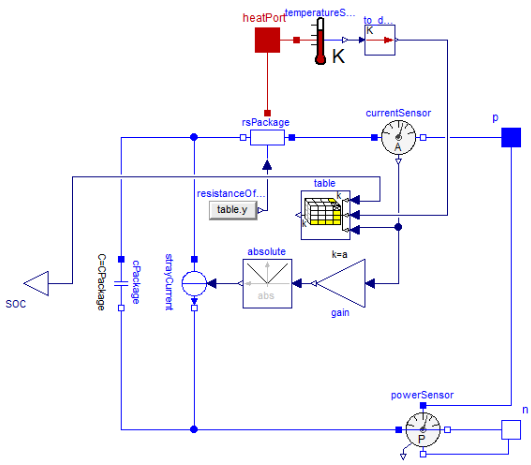

Figure 4: ERS equivalent circuit battery model

2.3 Cooling System Model

The cooling system for the engine and for the ERS can be incorporated into the model. Figure 4 shows the inclusion of the Engine cooling system which is modelled as a distributed capacitance heat transfer and 1D thermofluid system network as shown in Figure 5. The level of detail in each of the components can be varied to support simple sizing studies as well as the detailed investigation of heat exchanger geometries and stacking effects.

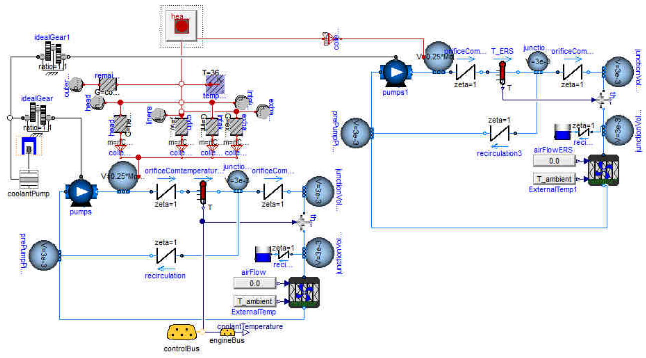

Figure 5: Engine Cooling System modelled as a 1D thermofluid system. Engine cooling on left and ERS cooling loop on right.

2.4 Transmission and Driveline Model

In this example the focus of the modelling effort has been on the engine, ERS and chassis systems with the aim of achieving real-time simulation. The transmission and driveline models are, therefore, low fidelity models with idealised shift dynamics. Using other Modelica libraries like the Powertrain Dynamics Library [9] it would be possible to include more detailed models.
Using the Powertrain Dynamics Library it would be possible to include detailed models of the transmission and driveline to capture the full torsional response of this system including the shift dynamics. An example gearbox model is shown below in Figure 6 that includes the individual bearings with friction, mesh points with efficiency, stiffness and backlash and torsional compliance in all the shafts.

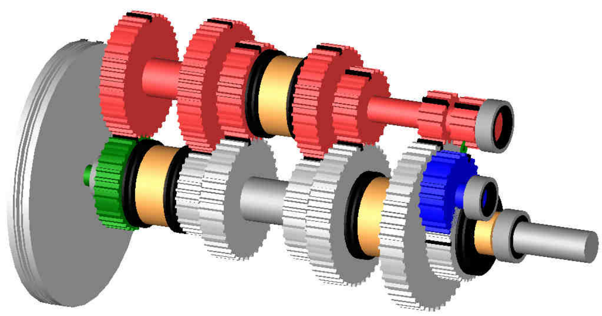

Figure 6: Animation of a gearbox model in Dymola

The VDLMotorsports Library has been used to create a full multibody chassis model, the architecture of which is shown in Figure 6. A similar application of this library is described in [7]. The library contains a number of double wishbone suspensions with pushrod and pullrod examples with different rocker arrangements for anti-roll and heave control. The compliance in the chassis can also be optionally modelled.

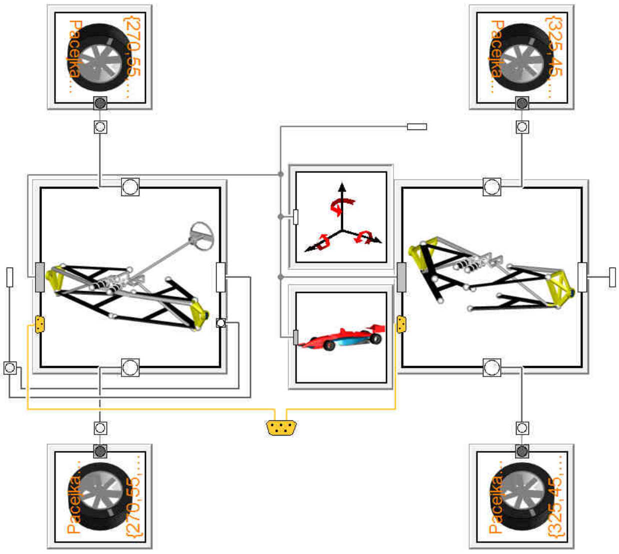

Figure 7: Chassis model

The suspension model incorporates the adjustments to enable the suspension setup to be defined in a realistic manner. Once the basic geometry of the suspension is defined the characteristics can be adjusted by changing the shim thickness in the pushrod and suspension links. The library contains setup experiments for determining the adjustment shims and preloads required to achieve the desired suspension setup.
The tyre model uses the Pacejka 2002 tyre slip model to calculate tyre forces. The model architecture for the tyre makes it very easy to replace this slip model with your own in-house model that could be written in Modelica or as C-code and linked to Dymola.
Aerodynamic effects are included in the car body model, which features separate aerodynamic models for the body, front and rear wings and tyres. Simple aerodynamic models are used based on coefficients but these can easily be extended to use available aerodynamic data.

3. Experiments

Dymola enables the use of the models in a wide variety of ways to maximise the reuse of the model through its application to different types of analysis and deployment in to 3rd party applications.
Within Dymola the created model, or any of the subsystem models, can be used in an experiment to investigate their behaviour. Dymola's acausal modelling methodology means that the same model can be used without modification in many different simulations to explore different aspects of the behaviour.
The thermal aspect of the ERS system was investigated as from early testing this was proving to be a major area of concern. Adequate sizing of the ERS cooling packs in relation to the duty cycles and control strategy approach used is key to being able to maintain required levels of performance from the components as any de-rating due to excessive component temperatures would result in reduced vehicle performance. The reduction in vehicle performance would result from a reduction in MGUK assist, delivering and recovering reduced torque to the crankshaft and a reduction in MGUH assist, compromising the potential to reduce turbo-lag and throttle response.

To investigate the thermal and performance sensitivity of the system the following tests were ran on a lap of the Silverstone Race track:

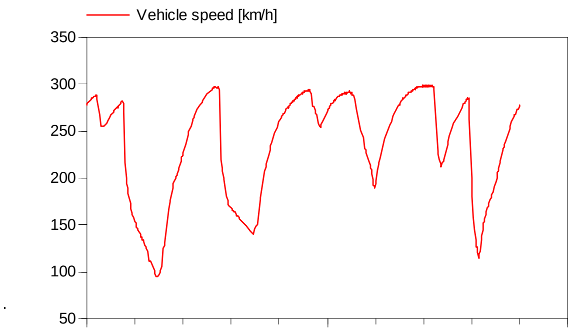

Figure 8: Speed-time trace of a lap of the Silverstone race track, UK.

The results are compared to a baseline test with SOC = 85%. Due to confidentiality, % improvements and detriments have been used in place of numerical values.

1. Increase of battery internal resistance due to possible cell failure
2. Variation of the cooling fluid temperature for the ERS system (23, 48.8 and 63 degrees) for 2 different states of charge (55% and 85%)
3. Reduction and increase of MGUK performance for both regen and assist
4. Reduction and increase of MGUH performance for both regen and assist

Scenario 1

Battery packs can be prone to a range of failure modes one of which relates to single, or in worse cases multiple cell failures. In these situations we can expect the internal resistance of the cell to increase hence generating more heat within the battery. This additional heat due to cell failure needs to be dissipated effectively to prevent thermal damage to the rest of the battery pack and also to limit de-rating of the ERS.
Running with the battery internal resistance up by 20% yielded and increase in overall ERS heat rejection of 7.32%.

In the overall ERS heat rejection we also include the electrical drives and controllers.

Scenario 2

In order to investigate how the battery performance and heat release can be affected by coolant temperatures we ran the vehicle on a circuit lap with 3 different ERS coolant temperatures: 23, 48.8 and 63 degC. The 3 runs were performed with an initial SOC of 85% and 55%. The characteristics of the battery used in the modelling showed a generally higher internal resistance with a lower SOC and lower operating temperatures. The interest therefore was to simulate a lap of the circuit with the two SOCs afore mentioned to understand what the consequences might be in terms of heat output from the battery.
All tests at 85% SOC showed that an increase in ERS coolant temperature yielded a reduction in heat output from the battery due to a drop in internal resistance of the cells within the battery. 48.8 and 63degC ERS coolant temperatures yielded a drop of heat energy output from the battery of 2.09% and 3.31% respectively. In the 63degC case, an extra 6.02% of electrical energy was deployable during the lap simulation.
The initial SOC was then dropped to 55% to investigate the implications of such a situation with the chosen battery chemistry. In all 3 ERS coolant temperature cases the heat output significantly increased by 42.23%, 36.95% and 33.51% respectively indicating a highly inefficient working region for the battery. The harvested electrical energy was reduced by 3.97%, 3.54 and 3.22% respectively due to the higher losses and battery internal resistance.

Scenario 3

Provided we remained within the battery charging and discharging limits set by the FIA, the amount by which the MGUH and MGUK regen and assist will be partly limited by the heat dissipation from the ERS devices. In particularly hot ambient scenarios this might be difficult to achieve especially during low speed situations on the track or even when closely following another vehicle which in turn will be leaving a trail of warmer air behind it from the heat exchange to ambient of its subsystems.
We simulate a lap of the circuit by reducing the MGUK assist and regen by 10% to understand what might be the impact on the heat released but also the consequences on lap time, energy harvested and savings in electrical energy deployed. The reduction in total ERS heat energy output was 8.9% , the reduction in energy harvested 8.79% and the reduction in total electrical energy deployed of 5.55%. The lap time deficit amounted to 0.15s.
The next simulation runs the opposite: +10% MGUK assist and regen. Compared to the baseline we generate 8.42% more total heat rejection, 8.48% increased electrical energy harvested and 8.48% increased useful energy out of battery. The laptime showed a reduction of 0.14s.
We then looked at increasing the regen and assist of the MGUH, first by 10% then by 20% over the baseline. This generated 2.73% and 5.11% increase in heat energy released by the ERS system respectively. The energy harvested was virtually unchanged but we do see a reduction of battery electrical energy deployed of 1.94% and 3.52% respectively. Lap times show marginal reduction of 0.02s and 0.04s respectively.
Finally on the electric drive tests we increased both the MGUK and MGUH assist and regen by 10%. The result of this strategy caused an increase in ERS thermal energy dissipated of 10.88% over the baseline, an increase of harvested and deployed electrical energy of 8.49% and 6.24% respectively. The lap time was reduced by 0.15s.

4. Discussion

The results for increasing the internal resistance of the battery by 20% to understand potential impacts of failing cells showed that the ERS heat energy release was substantially increased and that the useful harvested energy showed a drop of nearly 1%. Deployed energy showed negligeable change over the baseline and the reason for this will require further investigation.

Testing the thermal system performance on lower SOCs yielded interesting results where the battery was operating in a highly non-optimal region. The internal resistance of the battery in this region was significantly higher than SOC=85%. The internal resistance of the battery used in the tests is non-linear and varies in characteristics with charge and discharge, hence careful design of control algorithms must be applied for all situations making a distinction as to whether the battery is being charged or discharged. Charging the battery at a low state of charge might not yield the same heat losses than charging the battery and vice versa.

During the MGUH/MGUK tests we noticed that a significant amount of the energy generated by the MGUH during acceleration was directly channelled to the MGUK, bypassing the battery. This in turn caused the harvested energy not to increase. We did see however an increase in deployed energy which we think could be due to accelerating the inertia of the turbocharger electric motor in assist mode.
Lap times were generally improved by increasing the assist of the MGUK although a small reduction in lap time (0.02-0.04s) was also possible by increasing the assist of the MGUH. This also reduced the lag of the turbocharger spooling. The biggest reduction in heat released is achieved though reduction of the regen and assist through the MGUK (0.89% kWh / % reduction in MGUK assist and demand).

Conclusions

In this paper we have shown how a complete 2014 spec Formula 1 car model including the powertrain and chassis can be simulated to better understand the integration between all the subsystems, in this case the thermal aspects and performance aspects. The simulations can help to improve the thermal management of the systems and understand the resulting impact on lap times. These simulations can also help sixe components such as cooling pumps and heat exchangers which are fundamental for the optimal functioning of the electrical and mechanical drive components. Different cooling configurations and layouts can be explored.

Acknowledgements

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